

# The $\bar{d}$ $\bar{u}$ asymmetry of the proton in a pion cloud model approach

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## Abstract

We study the  $\bar{d}$   $\bar{u}$  asymmetry of the proton in a model approach recently developed, in which hadronic fluctuations of the nucleon are generated through gluon splitting and recombination mechanisms. Within this framework, it is shown that both  $\bar{d}/\bar{u}$  and  $\bar{d} - \bar{u}$  distributions in the proton can be consistently described by including only nucleon fluctuations to  $|\pi N\rangle$  and  $|\pi \Delta\rangle$  bound states. Predictions of the model closely agree with the recent experimental data of the E866/NuSea Collaboration.

In 1991, the New Muon Collaboration (NMC) [1] presented a determination of the non-singlet structure function  $F_2^p - F_2^n$  at  $Q^2 = 4 \text{ GeV}^2$  over the range  $0.004 < x < 0.08$ . From this measurement, the Gottfried Sum Rule (GSR) [2] was estimated and a

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significantly lower value than the  $1/3$  predicted by the quark-parton model was found. Although it could be due to an abnormal behavior of the valence quark distributions in the unmeasured region [3], the above result was attributed to a  $\bar{d}-\bar{u}$  asymmetry in the light nucleon sea (see e.g. Ref. [4]). Later on, the NA51 Collaboration [5] determined the value  $\bar{d}/\bar{u} = 1.961 \pm 0.252$  at  $x = 0.18$  in Drell-Yan dimuon production, giving strong experimental support to the  $\bar{d}-\bar{u}$  asymmetry explanation.

Most recently, the E866/NuSea Collaboration measured the ratio  $\bar{d}/\bar{u}$  in the nucleon over the range  $0.02 < x < 0.345$  in Drell-Yan dimuon production from  $p-p$  and  $p-D$  interactions [6]. From this measurement, the E866/NuSea Collaboration extracted the  $x$  dependence of  $\bar{d}-\bar{u}$  and estimated a value for its integral,  $\int_0^1 dx[\bar{d}-\bar{u}] = 0.100 \pm 0.018$ , indicating a strong GSR violation. Notably, this value is only about two thirds of the NMC estimate for the same integral,  $0.147 \pm 0.026$ . We will address this issue later on.

In conclusion, although a  $\bar{d}-\bar{u}$  asymmetry in the nucleon sea has been firmly established from experiments, its origin and precise features are yet unclear. Several ideas have been put forward to try to explain the GSR violation and the  $\bar{d}-\bar{u}$  asymmetry in nucleons. Among them the Pauli exclusion principle, which would inhibit the development of up (down) quarks and anti-quarks in the proton (neutron) sea, a pioneer idea by Field and Feynman [7]; fluctuations of valence quarks into quarks plus massless pions [8], an effect which is calculable in Chiral Field Theory; and earlier versions of the Pion Cloud Model (PCM) [9]. However, none of these attempts gave a satisfactory description of the experimental status of *both*  $\bar{d}-\bar{u}$  and  $\bar{d}/\bar{u}$  distributions. It should be noted that previous versions of the PCM used rather hard pion distributions inside the nucleon resulting in large  $\bar{u}$  and  $\bar{d}$  distributions beyond  $x \sim 0.3$ . These large pion contributions can not be easily compensated to conveniently describe the fast fall-off of  $\bar{d}-\bar{u}$  in the whole  $x$  range. Albeit large for small  $x$ , the  $\bar{d}-\bar{u}$  distribution seems to be negligible beyond  $x \sim 0.3$ . In addition, the  $\bar{d}/\bar{u}$  ratio predicted by these models exhibits a dramatic growing behavior not seen

in the experimental data. For reviews, see Ref.[10]

In this work we will show that a recently proposed version of the Pion Cloud Model (PCM) [11] allows a remarkable prediction of the nucleon's  $\bar{d} \bar{u}$  asymmetry in accordance with the recent results of the E866/NuSea Collaboration. Our approach is based on both perturbative and effective degrees of freedom, and it relies on a recombination model description of the hadronic fluctuations of the nucleon.

Let us briefly recall the model introduced in Ref. [11]. We start by considering a simple picture of the ground state of the proton in the infinite momentum frame as formed by three valence quark clusters or *valons* [12]. The valon distributions in the proton are given by

$$v(x) = \frac{105}{16} \sqrt{x} (1-x)^2, \quad (1)$$

where, for simplicity, we do not distinguish between  $u$  and  $d$  valons.

The higher order contributions to the proton structure are identified with meson-baryon bound states in an expansion of the nucleon wave-function in terms of hadronic Fock states. Such hadronic fluctuations are built up by allowing that a valon emits a gluon which, before interacting with the remaining valons, decays perturbatively into a  $q\bar{q}$  pair. This quark anti-quark pair subsequently recombines with the valons so as to form a meson-baryon bound state.

The probability distributions of the initial perturbative  $q\bar{q}$  pair can be calculated by means of the Altarelli-Parisi [13] splitting functions:

$$P_{gq}(z) = \frac{4}{3} \frac{1 + (1-z)^2}{z}, \quad P_{qg}(z) = \frac{1}{2} (z^2 + (1-z)^2). \quad (2)$$

Accordingly, the joint probability density of obtaining a quark or anti-quark coming from subsequent decays  $v \rightarrow v + g$  and  $g \rightarrow q + \bar{q}$  at some fixed low  $Q_v^2$  is

$$q(x) = \bar{q}(x) = N \frac{\alpha_{st}^2(Q_v^2)}{(2\pi)^2} \int_x^1 \frac{dy}{y} P_{qg}\left(\frac{x}{y}\right) \int_y^1 \frac{dz}{z} P_{gq}\left(\frac{y}{z}\right) v(z). \quad (3)$$

The value of  $Q_v$ , as dictated by the valon model of the nucleon, is about  $Q_v = 1$  GeV. For definiteness we take  $Q_v = 0.8$  GeV as in Ref. [11, 12], which is large enough to

allow for a perturbative evaluation of the  $q\bar{q}$  pair production.  $N$  is a normalization constant whose value depends on the flavor of the quark and anti-quarks produced in the  $gq\bar{q}$  vertex.

Once  $q$  and  $\bar{q}$  are created, they may subsequently interact with the valons so as to form a most energetically favored meson-baryon bound state. The rearrangement of such five-component nucleon configuration into a meson-baryon bound state must be evaluated by means of effective methods. This is necessary because the interactions involved in such a process are within the confinement region of QCD. Therefore, non-perturbative interactions take place. Assuming that the *in-proton* meson and baryon formation arise from mechanisms similar to those at work in the production of real hadrons, we evaluate the in-proton pion probability density using a well-known recombination model approach [14].

Within this scheme, the pion probability density in the  $|\pi B\rangle$  fluctuation of the proton is given by

$$P_{\pi B}(x) = \int_0^1 \frac{dy}{y} \int_0^1 \frac{dz}{z} F(y, z) R(x, y, z), \quad (4)$$

where  $R(x, y, z)$  is the recombination function associated with the pion formation,

$$R(y, z) = \alpha \frac{yz}{x^2} \delta\left(1 - \frac{y+z}{x}\right), \quad (5)$$

and  $F(y, z)$  is the valon-quark distribution function given by

$$F(y, z) = \beta y v(y) z \bar{q}(z) (1 - y - z)^a. \quad (6)$$

The exponent  $a$  in eq. (6) is fixed by the requirement that the pion and the baryon in the  $|\pi B\rangle$  fluctuation have the same velocity, thus favoring the formation of the meson-baryon bound state. With the above constraint we obtain  $a = 12.9$  and  $a = 18$  for the  $|\pi^+ n\rangle$  and the  $|\pi \Delta\rangle$  fluctuations of the proton respectively.

Note that in the original version of the recombination model this exponent was fixed to 1 [14]. This is basically because in a collision, the only relevant kinematical

correlation in the model between the initial and final states is momentum conservation. On the other hand, in the present case the recombining quarks are more correlated as they are making part of a single object from the outset. Firstly, meson and baryon must exhaust the momentum of the proton<sup>1</sup>, and secondly, they must be correlated in velocity as a bound-state is expected to be formed.

The overall normalization  $N\beta\alpha$  of the probability density  $P_{\pi B}$  must be fixed by comparison with experimental data.

The non-perturbative  $\bar{u}$  and  $\bar{d}$  distributions can now be computed by means of the two-level convolution formulas

$$\bar{d}^{NP}(x, Q_v^2) = \int_x^1 \frac{dy}{y} \left[ P_{\pi N}(y) + \frac{1}{6} P_{\pi \Delta}(y) \right] \bar{d}_\pi\left(\frac{x}{y}, Q_v^2\right) \quad (7)$$

$$\bar{u}^{NP}(x, Q_v^2) = \int_x^1 \frac{dy}{y} \frac{1}{2} P_{\pi \Delta}(y) \bar{u}_\pi\left(\frac{x}{y}, Q_v^2\right), \quad (8)$$

where the sources  $\bar{d}_\pi(x, Q_v^2)$  and  $\bar{u}_\pi(x, Q_v^2)$  are the valence quark probability densities in the pion at the low  $Q_v^2$  scale. In eq. (7), we have summed the contributions of the  $|\pi^+ n\rangle$  and  $|\pi^+ \Delta^0\rangle$  fluctuations to obtain the total non-perturbative  $\bar{d}$  distribution. For the non-perturbative  $\bar{u}$  distribution of eq. (8), the only contribution originates from the  $|\pi^- \Delta^{++}\rangle$  fluctuation. Contributions arising from fluctuations containing neutral mesons as the  $\pi^0$ , are strongly suppressed in this model and will not be considered<sup>2</sup>.

We also neglect higher order Fock components.

The factors  $\frac{1}{6}$  and  $\frac{1}{2}$  in front of  $P_{\pi \Delta}$  in eqs. (7) and (8) are the (squared) Clebsh-

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<sup>1</sup>We fulfill this requirement by assuming  $P_{\pi B}(x) = P_{B\pi}(1-x)$ . See Ref. [11] for a discussion about this point.

<sup>2</sup>This suppression is associated with their flavor structure (in terms of their parton components). In particular for  $\pi^0 \simeq (d\bar{d} - u\bar{u})$  fluctuations. In our model the first component arises from the recombination of a  $\bar{d}$  quark and a  $d$  valon, and the second comes from the recombination of a  $\bar{u}$  quark and a  $u$  valon. Due to their unflavored structure, neutral in-nucleon quark-antiquark objects would tend to be annihilated much more rapidly than charged, flavored ones like  $u\bar{d}$  or  $d\bar{u}$ . In other words, unflavored  $q\bar{q}$  recombination would be highly inhibited and neutral pion fluctuations would be ephemeral. Thus,  $\pi^0$  configurations would be unlikely to occur in comparison with  $\pi^\pm$  fluctuations, although they belong to the same mass multiplet.

Gordan (CG) coefficients needed to account for the  $\frac{1}{2}$  isospin constraint on the fluctuation. The CG coefficient corresponding to the  $|\pi^+ n\rangle$  fluctuation is hidden in the global normalization of the state.

We will now compare our results with the experimental data. As the E866/NuSea Collaboration measures the ratio  $\bar{d}/\bar{u}$  at  $Q = 7.35$  GeV, we first compute this quantity by means of

$$\frac{\bar{d}(x, Q^2)}{\bar{u}(x, Q^2)} = \frac{\bar{d}^{NP}(x, Q^2) + \bar{q}^P(x, Q^2)}{\bar{u}^{NP}(x, Q^2) + \bar{q}^P(x, Q^2)} . \quad (9)$$

Here  $\bar{d}^{NP}(x, Q^2)$  and  $\bar{u}^{NP}(x, Q^2)$  are given by eqs.(7) and (8) and  $\bar{q}^P(x, Q^2)$  represents the perturbative part of the up and down sea of the proton, which we assume to be equal. This assumption is exact up to at least 1% [15].

Regarding the difference  $\bar{d} - \bar{u}$ , instead of computing it directly by subtracting eqs. (7) and (8), we will extract it from the  $\bar{d}/\bar{u}$  ratio as done in Ref. [6]. In its paper, the E866/NuSea Collaboration employed the following identity to obtain the difference:

$$\bar{d}(x) - \bar{u}(x) = \frac{\bar{d}(x)/\bar{u}(x) - 1}{\bar{d}(x)/\bar{u}(x) + 1} [\bar{u}(x) + \bar{d}(x)] . \quad (10)$$

While the ratio  $\bar{d}(x)/\bar{u}(x)$  is a direct measurement of E866 the sum  $\bar{u}(x) + \bar{d}(x)$  appearing in eq. (10) is taken from the CTEQ4M parametrization [16].

In Fig. 1, our predictions of  $\bar{d}/\bar{u}$  and  $\bar{d} - \bar{u}$  are compared with the experimental data from Ref. [6]. The curves were obtained using the pion valence distributions of Ref. [17] in eqs. (7) and (8) and the proton sea quark distributions of Ref. [18] in eq. (9).

Note that a rigorous comparison of our prediction with the experimental data would require that the non-perturbative  $\bar{u}$  and  $\bar{d}$  distributions be evolved up to  $Q = 7.35$  GeV. Instead of performing a full QCD evolution program, we *pseudo-evolve* the  $\bar{u}^{NP}$  and  $\bar{d}^{NP}$  distributions by multiplying them by the ratio  $q(x, Q^2 = 7.35^2 \text{ GeV}^2)/q(x, Q_v^2)$ . The function  $q$  represents the corresponding valence quark distribution in the proton at the E866/NuSea and the valon scales respectively. This simple procedure is satisfactory enough to give us a feeling of the effect of the evolution of

the non-perturbative distributions on  $\bar{d}/\bar{u}$  and  $\bar{d} - \bar{u}$  <sup>3</sup>.

As can be seen in Fig. 1, the results of the model are impressive, considering that we are representing *both* the difference and the ratio. Nevertheless, in the small- $x$  region the model seems to overestimate the value of  $\bar{d} - \bar{u}$  due to the steep growth of the valence quark distribution of the pion as  $x \rightarrow 0$ . If for instance, we multiply the quark distribution of the pion by a power of  $x$ ,<sup>4</sup> the signaled excessive growth at very small  $x$  is corrected while the rest of the curve does not appreciably changes. The  $\bar{d} - \bar{u}$  difference predicted by the model at the valon scale  $Q_v$  thus presents an inflection point about  $x \sim 0.05$  and goes to zero with  $x$ . The description of the  $\bar{d} - \bar{u}$  data is thus improved at the price of having modified the low  $x$  behavior of the valence quark distributions in pions, a region where they are not well known. In addition, we also get a more accurate description of the  $\bar{d}/\bar{u}$  data in all the measured region (see Fig. 2). It should be noted that similar results are obtained by using the low  $Q^2$  pion valence quark distributions of Ref. [20], calculated with a Monte Carlo based model.

It is instructive to look at the integrals of the non-perturbative  $\bar{u}$  and  $\bar{d}$  distributions in order to get an idea of the relative weights of the  $|\pi N\rangle$  and  $|\pi \Delta\rangle$  fluctuations in the model. By fixing the normalization of the bound states to fit the experimental data, for the unevolved curves in Fig. 1 (Fig. 2) we have  $\int_0^1 dx \bar{u}^{NP}(x) \sim 0.28$  (0.15) and  $\int_0^1 dx \bar{d}^{NP}(x) \sim 0.47$  (0.29). Accordingly, the value of  $\int_0^1 dx [\bar{d}^{NP}(x) - \bar{u}^{NP}(x)]$  predicted by the model is 0.19 (0.14) <sup>5</sup>. This is in good agreement with the experimental result  $0.147 \pm 0.039$ , as given by the NMC [1].

If, on the other hand, we consider the definition of  $\bar{d}(x) - \bar{u}(x)$  as given by eq. (10), our prediction of  $\int_0^1 dx [\bar{d}^{NP}(x) - \bar{u}^{NP}(x)]$  is 0.091 (0.083), in close agreement with  $0.10 \pm 0.018$ , obtained by the E866/NuSea Collaboration [6]. Note that this value of the integral is significantly lower than the previous one, which we obtained by

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<sup>3</sup>A similar strategy has been adopted in Ref.[19]

<sup>4</sup>For simplicity we used a power 1, but other values close to this can do the job as well.

<sup>5</sup>Notice that, as an integral of a non-singlet quantity,  $\int_0^1 dx [\bar{d}(x) - \bar{u}(x)]$  is independent of  $Q^2$  [8]. Then, our results at the valon scale remain unchanged after QCD evolution.

direct integration of the difference between eqs. (7) and (8). This discrepancy is due to the modulation introduced by the CTEQ4M  $\bar{u}(x) + \bar{d}(x)$  distribution used by the E866/NuSea Collaboration to extract the  $\bar{d} - \bar{u}$  distribution <sup>6</sup>.

A similar analysis of the E866/NuSea data has been recently performed in the framework of a light cone form factor version of the pion cloud model [21]. Predictions of this version of the PCM are however not very close to the data. One reason may be the use of unnatural hard pion distributions in  $|\pi N\rangle$  and  $|\pi\Delta\rangle$  fluctuations, which produce large contributions to the  $\bar{u}$  and  $\bar{d}$  distributions beyond  $x \sim 0.25$ . This drawback in the prediction of  $\bar{d} - \bar{u}$  translates into the growing behavior of the resulting  $\bar{d}/\bar{u}$  ratio. To obtain an improved description of both  $\bar{d} - \bar{u}$  and  $\bar{d}/\bar{u}$  within this approach, the addition of an *ad-hoc* parametrization of the Pauli exclusion principle is needed. In particular, in Ref.[21], the Pauli effect is normalized to 7% while the total pion cloud contribution is just 5%. It means that the Pauli contribution would amount to a 58% of the total asymmetry. This is a major contrast between this approach and the present work.

Summarizing, we have shown that, including perturbative and effective degrees of freedom in a recombination scheme, a pion cloud model alone closely describes the recent data of the E866/NuSea Collaboration. With just two parameters, the normalization of the  $|\pi N\rangle$  and  $|\pi\Delta\rangle$  fluctuations, we have presented an accurate prediction of the flavor asymmetry in the light nucleon sea. Remarkably, our model results allow an excellent fit of both distributions, difference and ratio, in a consistent way. Finally, we have also signaled a possible reason for the apparent discrepancy between E866/NuSea and NMC results on the GSR violation.

Note added: After the conclusion of this paper another PCM evaluation of both difference and ratio has been performed [22]. In contrast to ours it is based on the use of form factors. For the chosen parameters a reasonable fit of the difference is

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<sup>6</sup>See also Ref. [6] for an additional discussion about the discrepancies between E866/NuSea and NMC results.



obtained but the model predictions for the ratio  $\bar{d}/\bar{u}$  do not fit the experimental data.

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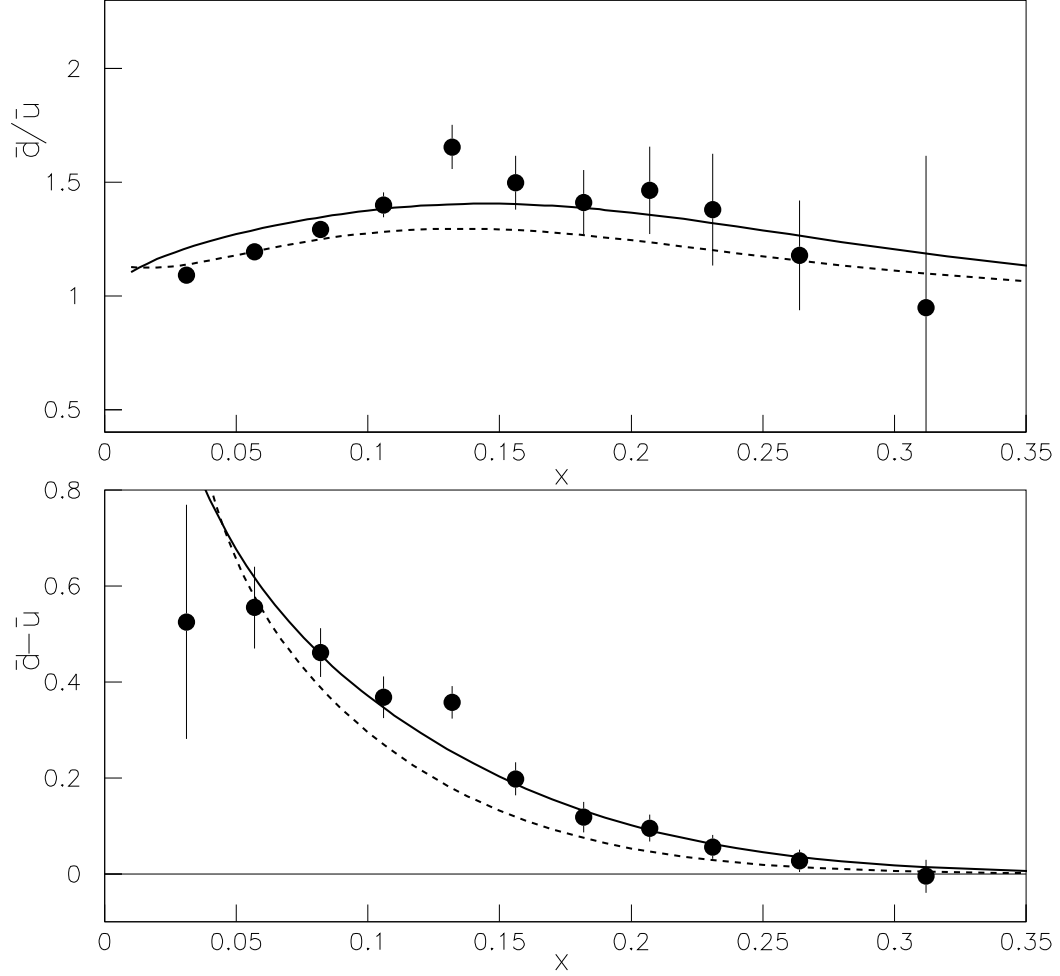


Figure 1: Predictions of the model compared with experimental data from Ref. [6].  $\bar{d}/\bar{u}$  ratio (upper) and  $\bar{d}-\bar{u}$  asymmetry (lower) at  $Q = 7.35$  GeV. Curves are calculated with unevolved  $\bar{u}^{NP}$  and  $\bar{d}^{NP}$  distributions (full line) and with pseudo-evolved non-perturbative distributions (dashed line)

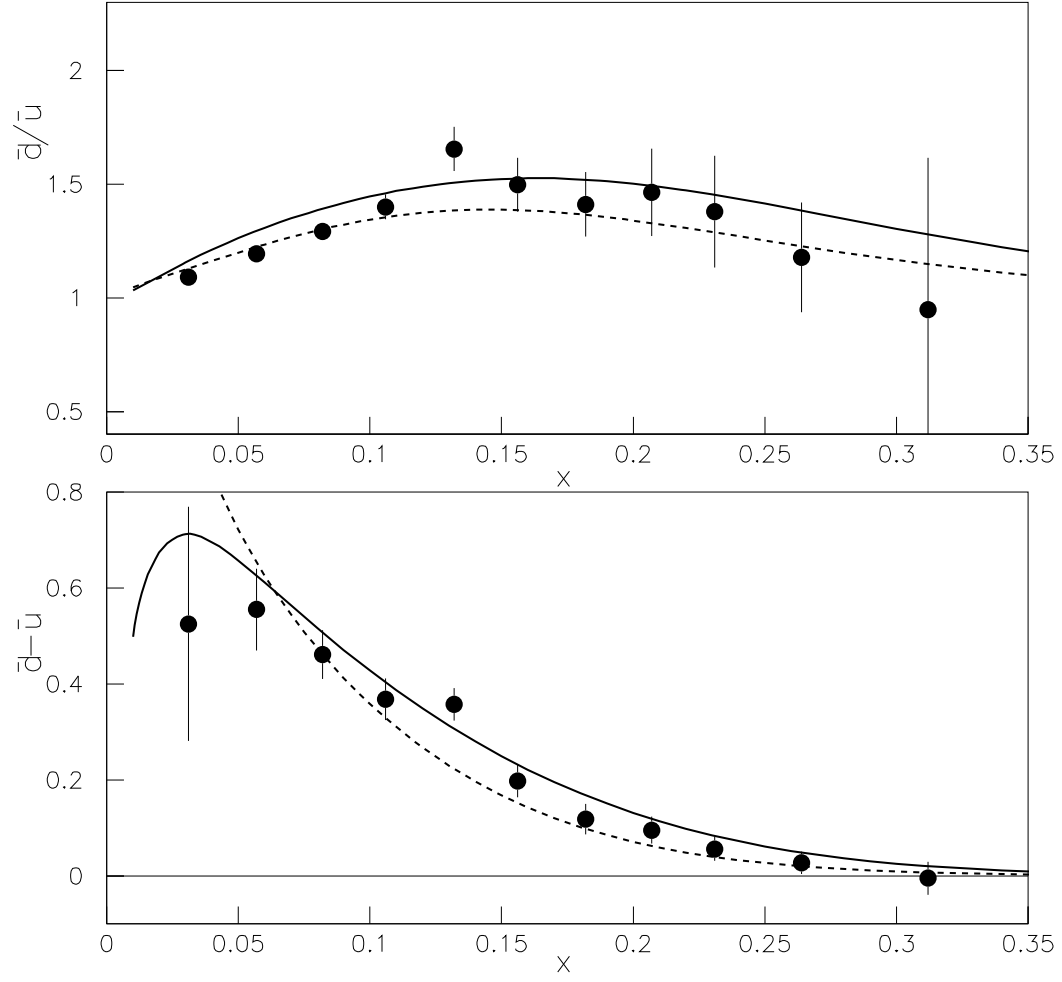


Figure 2: Same as in Fig. 1 but using a modified valence quark distribution in pions with an extra power of  $x$  (normalized accordingly). See discussion in the text.